Aalto University School of Electrical Engineering

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Abstract

Sleep problems are one of the most common medical complaints today. Polysomnography (PSG) as the current standard for sleep analysis is expensive, intrusive and complex. Thus, finding a reliable and unobtrusive method for longer-term home use is important. Ballistocardiography (BCG) based methods have shown potential in sleep analysis recently. The usability and performance of a BCG based method in qualitative and quantitative analysis of sleep was evaluated. The method was validated in a clinical test on 20 subjects using PSG as a reference. Heart rate (HR), heart rate variability (HRV), respiratory rate (RR), respiratory rate variability (RRV), respiratory depth (Rdepth) and movement were utilized for sleep stage detection.

The BCG parameter accuracy was presented as the mean error from PSG with 95% confidence interval. The errors were -0.1 $\pm$ 4.4 beats per minute for HR, -0.9 $\pm$ 14.7 ms for high frequency (HF) HRV, -3.0 $\pm$ 29.9 ms for low frequency (LF) HRV, 0.3 $\pm$ 4.5 breaths per minute for RR and -40 $\pm$ 424 ms for RRV respectively. Correlation coefficient was 0.97 for HR, 0.67 for HF HRV, 0.71 for LF HRV, 0.54 for RR and 0.49 for RRV. HR, RRV and Rdepth were typically at an increased level in REM sleep and wakefulness and decreased in deep sleep. RRV was at its highest during wakefulness. HRV was at a decreased level in REM and wakefulness and increased in deep sleep. Movement was higher during wakefulness than in sleep.

Keywords ballistocardiography, polysomnography, sleep quality

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Preface

This report presents findings from the sleep study on *Nocturnal Sleep Quality and Quantity Analysis with Ballistocardiography*. It summarizes the experimental part of the author's master's thesis on the subject. [1] The study was conducted for Aalto University School of Electrical Engineering in collaboration with the University of Turku and Murata Electronics Oy (MFI). M.Sc. (Tech.) Sami Nurmi organized the study and wrote the thesis and this report for Aalto University. MD, Ph.D. Tarja Saaresranta was responsible for the study and M.Sc. (Tech.) Tero Koivisto acted as the project manager from the University of Turku. M.Sc. (Tech.) Ulf Meriheinä provided the support for the project from Murata Electronics Oy and similarly D.Sc. (Tech.) Lauri Palva contributed from Aalto University School of Electrical Engineering.

Espoo, 23.05.2016

Sami Nurmi

Introduction

Sleep problems are increasing in our society and they are one of the most common medical complaints today. Sleep disorders can have a severe impact on the health and quality of life if they are not treated. Sleep is an unconscious state and therefore sleep problems may easily remain unrecognised without proper analysis. [2][3]

Polysomnography (PSG) is currently the primary method used in sleep analysis. However, it is expensive, intrusive and complex. An overnight sleep study can cost well over half a thousand euros. Accurate measuring requires laboratory environment and multiple sensors placed on the body. The monitoring and analysis is performed by highly trained technicians and doctors and the sleep is visually analyzed from the measurement signals. Although PSG gives a lot of information about sleep, it does not provide a normal environment and is not suitable for continuous long-term measurements. [4]

Finding new ways to measure sleep effectively has become more important as it has been proven that sleep has a large impact on the health and everyday life. Ballistocardiography (BCG) based methods have shown increasing potential for sleep analysis. [5][6] BCG measures the mechanical forces originating from the body. It is an inexpensive and unobtrusive method that is also viable for long-term use. It enables pre-emptive detection of sleep problems and effective post-monitoring of recovery. In this study, the usability and performance of an accelerometer based BCG method was evaluated for sleep analysis. [1]

Measurements

A clinical test was performed in order to validate cardiac and respiratory parameters of Murata BCG sensor product and define the parameter characteristics in sleep stages. PSG method was used as a reference. The test group consisted of 20 subjects with 17 men and 3 women. Healthy 24 - 46 year old adults were included. Subjects consuming excessive amounts of caffeine or alcohol, experiencing sleep problems, restless legs syndrome (RLS), grinding of teeth, loud snoring or using medication with CNS effects were excluded from the test. The tests included overnight measurements of sleep with the BCG and PSG devices in a sleep laboratory. Each test subject was measured for a single night.

Murata SCA11H BCG Sensor Node was used as the BCG measurement device [7]. The BCG node (83.7 mm x 40.7 mm x 17.6 mm) consists of Murata SCA10H BCG Sensor Module, WiFi module and a power cord. The module includes Murata SCA61T accelerometer and a microprocessor. The analog one-axis accelerometer detects the BCG signal with a resolution of 90 μg and operates with 1 kHz sampling frequency. The detected acceleration signal can be processed with an intelligent algorithm in real time. The BCG algorithm reports multiple parameters at 1 Hz frequency. The output parameters in BCG mode are timestamp, heart rate (HR), respiratory rate (RR), relative cardiac stroke volume (SV), heart rate variability (HRV), signal strength, bed occupancy status and beat-to-beat intervals (b2b). The BCG node was attached under the bed mattress with another node as a backup, as seen in the section a) of Figure 1.

Figure 1. Left: a) BCG equipment setup. Right: b) PSG equipment setup. [1]

The PSG equipment provided measurement signals from a total of 18 channels. Six electrodes were used for the measurement of brain activity with electroencephalography (EEG), two electrodes for the measurement of eye movements with electro-oculography (EOG) and two electrodes for the measurement of mandibular muscle tension with electromyography (EMG). Three electrodes were used to measure cardiac function with electrocardiography (ECG). Thorax and abdomen belts were added to measure respiratory effort. Other devices included in the standard PSG setup, although not utilized in the analysis, were a TCM4 radiometer for transcutaneous CO_2 level detection, a finger-probe pulse oximeter to measure arterial oxygen saturation, and nasal prongs attached to a pressure sensor for nasal air flow and end-tidal CO_2 measurements. All devices were linked to a connector unit. A complete PSG equipment setup on a test subject can be seen in the section b) of Figure 1.

HR and HRV were calculated from the ECG signal. HRV at around 0.15

- 0.4 Hz was defined as the high frequency (HF) component and HRV at around 0.05 - 0.15 Hz as the low frequency (LF) component. RR and RRV were calculated from the thorax belt signal. Respiration depth (Rdepth) was related to the amplitude difference between expiration and inhalation peaks in the signal. Relative HRV was calculated according to Equation 1.

$$HRV = \frac{HFHRV}{LFHRV * Rdepth} \tag{1}$$

Rdepth was added in to filter out the HRV modulation caused by respiration.

The same parameters were calculated from the BCG recording. SV modulation was used to calculate the Rdepth. The parameters were synchronized by timestamp and low-pass filtered to be comparable to the respective BCG recordings.

Sleep stages were visually scored from the EEG, EOG and EMG recordings in 30 second epochs by a skilled technician. The American Academy of Sleep Medicine (AASM) criteria were used in the scoring [8]. The sleep stages were divided into light sleep, deep sleep, REM sleep and wakefulness periods. Typical levels of the BCG output parameters were calculated in each sleep stage. All 20 tests were individually processed in a similar way, and the data was compiled together for result analysis. [1]

Results

The RR, RRV, Rdepth, HR, HF HRV and LF HRV parameters, that were calculated from BCG and PSG recordings, were compared together for validation. Rdepth could not be detected accurately with the thorax belt due to the amplitude variations caused by test subject posture and movements. The mean error (μ), standard deviation (2σ) of the error and correlation (r) were calculated for the comparison of each parameter. The standard deviation was multiplied by two to define the maximum difference of the parameter values with 95 % confidence interval (CI). The results are presented in Table 1.

HR and HRV correlation to the reference were good ($r > 0.7$). The respiratory measurements with both, the PSG and BCG, methods were less accurate than the cardiac measurements. Due to this, RR and RRV correlation to the reference was slightly lower. However, the difference

Table 1. BCG parameter validation results for HR, HF HRV, LF HRV, RR and RRV. [1]

	Mean Error (μ)	95% CI (2σ)	correlation (r)
HR (bpm)	- 0.1	$\pm$ 4.4	0.97
HF HRV (ms)	- 0.9	$\pm$ 14.7	0.67
LF HRV (ms)	- 3.0	$\pm$ 29.9	0.71
RR (bpm)	0.3	$\pm$ 4.5	0.54
RRV (ms)	- 40	$\pm$ 424	0.49

between BCG and PSG measurements was not significant for any of the compared parameters.

Typical levels of HR, HRV, RR, RRV and Rdepth in each sleep stage were calculated. Figure 2 presents the results from a single night.

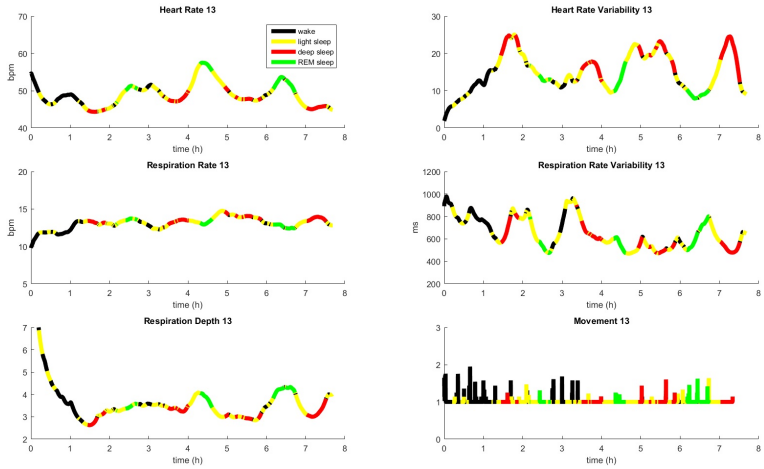

Figure 2. The levels of HR, HRV, RR, RRV, Rdepth and movement are graphically presented for one night. The sleep stages are indicated by colors. [1]

The typical parameter levels in the sleep stages are summarized in Table 2.

It can be seen that HR was typically at a high level during wakefulness and REM sleep compared to deep and light sleep. HRV was typically at the highest level during deep sleep and at the lowest in REM and wakefulness. There was no clear difference in RR between the sleep stages. RRV was typically at the lowest level during deep sleep and increased in REM and wakefulness. It was clearly higher in wakefulness compared to REM sleep. Rdepth was typically at the lowest level during deep sleep and at the highest level during REM and wakefulness. The detected movement from BCG was also added in the evaluation. There

Table 2. Typical HR, HRV, RR, RRV and Rdepth in each sleep stage. The levels have been categorized from the lowest to the highest as low, decreased, medium, increased and high. [1]

	Light Sleep	Deep Sleep	REM Sleep	Wakefulness
HR	Decreased	Decreased	Increased	Increased
HRV	Medium	Increased	Decreased	Decreased
RR	Medium	Medium	Medium	Medium
RRV	Medium	Low	Increased	High
Rdepth	Medium	Decreased	Increased	Increased

was significantly more movement during wakefulness than in sleep. [1]

Conclusions

The currently prevalent method for sleep analysis is PSG. However, it is too expensive, intrusive and complex for common use. PSG is mainly used for single night measurements in a laboratory environment. An accelerometer based BCG method for sleep analysis was evaluated in this work. BCG provides an inexpensive and unobtrusive way to measure sleep over multiple nights in home environment. Sleep can be measured with a single BCG device without attaching electrodes on the body or requiring skilled technicians for operation and maintenance. The first objective of this study was to validate the BCG ouput parameters on healthy subjects using PSG as a reference. The second objective was to test the BCG method for sleep analysis and evaluate the parameters in sleep stages.

A clinical test was prepared and performed on 20 healthy subjects in a sleep laboratory. Sleep was recorded overnight using Murata BCG Sensor Node and a PSG system. According to the results, the HR, HF HRV and LF HRV parameters measured with BCG were accurate and correlated well with the reference. RRV and Rdepth correlation to the reference was weaker but there was no significant difference between the BCG and PSG values. Rdepth was left out of validation due to inaccurate PSG measurement. The BCG parameters were reliable enough to be used for sleep analysis.

Typical HR, HRV, RR, RRV and Rdepth levels were calculated in four sleep stages: light sleep, deep sleep, REM sleep and wakefulness. HR was typically increased in REM sleep and wakefulness. HRV was typi-

cally decreased in REM and wakefulness and clearly increased in deep sleep. RRV was typically increased in REM and wakefulness. It was at the highest level in wakefulness and at the lowest level in deep sleep. Rdepth was typically decreased in deep sleep and increased in REM and wakefulness. Increased movement was detected in wakefulness compared to the sleep period. Movement and RRV could be used to distinguish REM sleep and wakefulness from each other. These parameters provided enough information to identify the sleep stages and differentiate between sleep and wakefulness.

Further studies should expand clinical testing of the Murata BCG sensor product. More diverse and extensive test groups could be selected. Increasing the amount of test subjects would give more credibility on the results. Future tests could include children, elderly people, and persons with detected sleep problems. These studies should focus on detecting insomnia, arrhythmias or disorders related to the respiratory system.

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